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NASA TM X-1659

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LIQUID REORIENTATION IN SPHERES BY MEANS OF LOW-G ACCELERATIONS

by Thomas L. Labus and William J. Masica

Lewis Research Center
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1968

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ABSTRACT

An experimental drop-tower investigation of liquid reorientation in spherical containers was conducted from two initial interface conditions. One initial condition was a centrally located vapor bubble (the interface configuration in a zero-Bond-number environment). A second initial condition was an essentially flat interface (the configuration in a relatively high-Bond-number environment). Liquid reorientation was observed to be axisymmetric under both initial conditions. Qualitative observations of the gross effects of percent liquid volume and acceleration on the reorientation process are presented. Also included are graphic profiles of the liquid-vapor interface at selected times during the reorientation process.

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SUMMARY

An experimental investigation of liquid reorientation in spherical containers (2. 1 to 3. 1 cm radii) by means of low-g accelerations (0. 005 to 0. 03 g) was conducted in the Lewis Research Center's 2. 3-second drop tower. The liquids used had zero-degree-static-contact angles on the spherical containers. The study was conducted at two initial conditions. One initial condition was a centrally located vapor bubble (i. e., the interface configuration in a zero-Bond-number environment). A second initial condition was an essentially flat interface (i. e., the configuration in a relatively high-Bond-number environment). In each case, the low-g acceleration or reorientation thrust resulted in a low reorientation Bond number ranging from 1. 6 to 23. Liquid reorientation was observed to be axisymmetric under both initial conditions. Qualitative observations of the gross effects of percent liquid volume and acceleration on the reorientation process are presented. Also included are graphic profiles of the liquid-vapor interface at selected times during the reorientation process.

INTRODUCTION

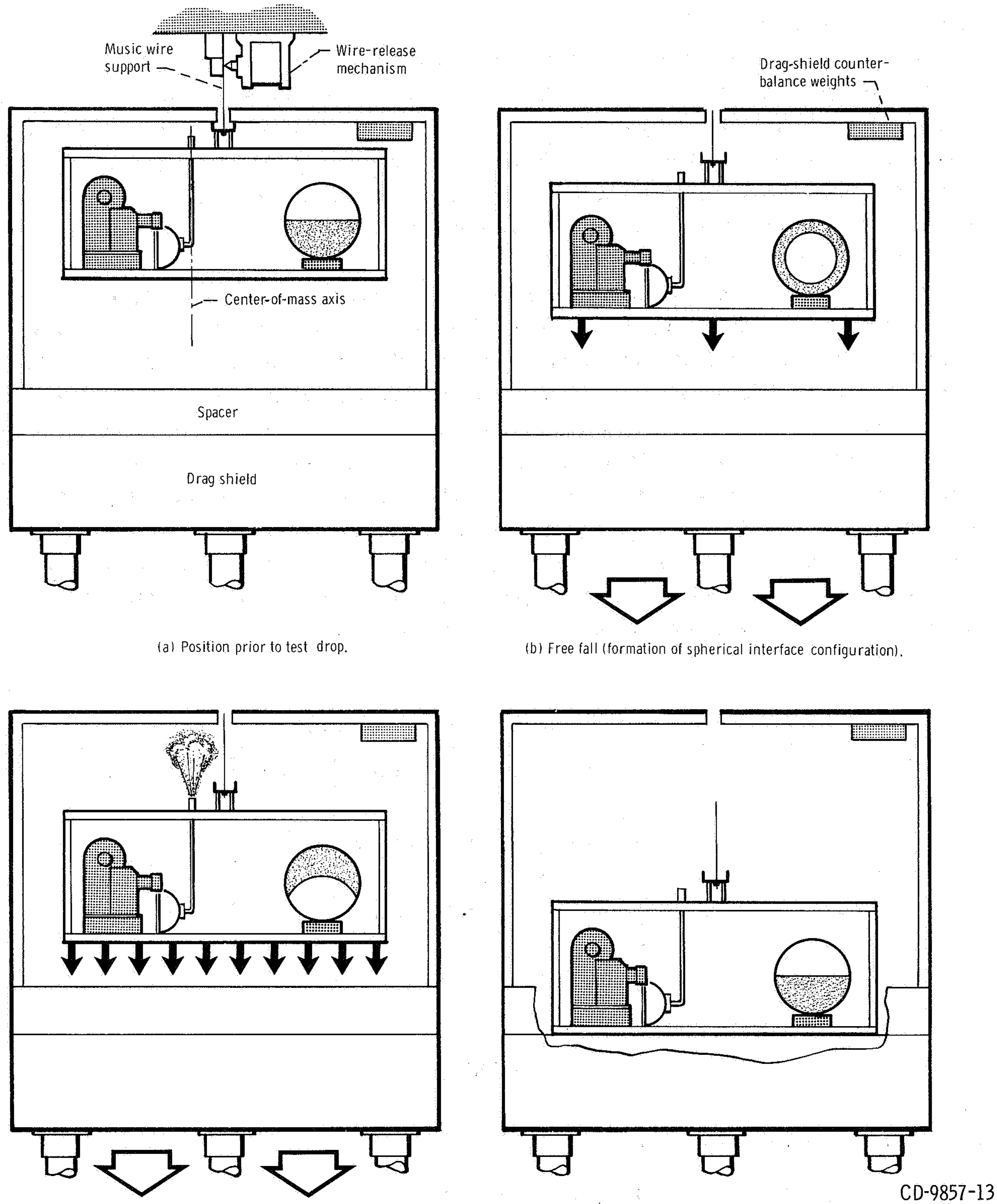
The major objectives of liquid-propellant management during coasting flight, where environments with a low-Bond number (ratio of acceleration to capillary forces) are frequently encountered, are to ensure reliable engine restart and, in the case of cryogenics, efficient venting to control tank pressurization. The use of small auxiliary thrusters has been proposed as one method of maintaining proper propellant orientation by inducing a low-g body force in the direction of main-engine thrust. The successful use of these auxiliary thrusters has been demonstrated during the short-term orbital flights of the Centaur (ref. 1) and of the S-IVB stage of the Saturn vehicle (ref. 2). In each of these flights, the continuous application of low-g accelerations and various baffle combinations maintained propellant orientation through the various kinetic energy inputs encountered during main-engine shutdown and the coasting flight. However, the continuous application of a low-g acceleration during long-term coast could cause excessive weight penalties. Thus, the application of such an acceleration may have to be reduced to intermittent periods. During the no-thrust periods, interface disruption and adverse relocation of the propellant due to shut-down transients, orientation maneuvers, residual drag, etc., could occur. In fact, for some propellant-tank geometries such as a sphere, even the absence of all kinetic energy inputs will still result in an undesirable propellant-vapor location during the zero-Bond-number, no-thrust periods. In these cases, the low-g auxiliary thrusters will be called upon to reorient or collect the propellant to the desired location prior to engine restart and venting. A thorough understanding of this reorientation mode by low-g accelerations is necessary for successful mission performance.

Studies of low-g liquid reorientation are found in references 3 to 7. In general, investigators of reorientation have been concerned solely with cylindrical propellant tank geometries. To our knowledge, no studies have been published describing low-g, liquid reorientation in spherical geometries.

The purpose of this report is to present the results of an experimental investigation of liquid reorientation in spheres (nominal radius of 2.5 cm) by low-g (0.005 to 0.03 g) accelerations. The experiments were conducted in the Lewis Research Center's 2.3-second drop-tower facility. Only liquids with static contact angles of essentially 0° were used. Two initial interface (or Bond number) conditions were studied. The first condition was a centrally located vapor bubble (i.e., the interface configuration in a zero-Bond-number environment). A second initial condition was an essentially flat liquid-vapor interface (i.e., the configuration in a relatively high (of order 10^2) Bond-number environment). In both cases, the low-g acceleration resulted in a low reorientation Bond number ranging from 1.6 to 23. The results indicate that axisymmetric reorientation flow patterns occur for both initial conditions. A qualitative discussion of the effects of reorientation acceleration and percent liquid volume on the reorientation process is presented. Also included are graphic profiles of the liquid-vapor interface at selected times during the reorientation process.

APPARATUS AND PROCEDURE

The investigation was conducted in the Lewis Research Center's 2.3-second drop-tower facility (ref. 8). The reorientation acceleration was imposed on the experiment by means of a high-response, gaseous-thrust system. Ground calibration, using a combined load cell and air bearing stand, determined the acceleration to within ±5 percent. The magnitude of the reorientation acceleration used in this investigation was from 0.005 to 0.03 g. The center of mass of the experiment package was located along the thrust axis, and the experiments were alined so that the reorientation acceleration was directed nor-



(a) Position prior to test drop.

(b) Free fall (formation of spherical interface configuration).

(c) Application of thrust (low-acceleration field).

(d) Position after test drop.

Figure 1. - Schematic drawing showing sequential position of experiment package and drag shield before, during, and after test drop.

mal to the liquid-vapor interface.

Aerodynamic drag on the experiment package was kept below 10^{-5} g by allowing the package to fall freely inside a protective drag shield, designed with a high ratio of weight to frontal area and a low drag coefficient. The drag shield was modified by use of interchangeable spacers to allow for the added relative displacement of the accelerated package. A schematic of the drag shield and experiment package assembly, along with the sequence of events under one particular initial interface condition (i.e., thrusting from a spherical interface), is shown in figure 1.

All data were recorded photographically and corrected for optical refraction. However, refraction corrections close to the container wall were only approximate; and, therefore, the corresponding thin liquid layer could not be measured accurately. In these cases, the data were corrected by using the known liquid volume. Time measurements were obtained by viewing a digital clock with a calibrated accuracy of 0.02 second.

Analytic-reagent-grade liquids were used. They formed static-equilibrium contact angles of 0° on their respective containers. The pertinent properties of these liquids are presented in table I. Acrylic-plastic spherical tanks, ranging in radius from 2.1 to 3.1 centimeters, were used in this study. The range of liquid volume was from 30 to 80 percent. The ranges of liquid properties, tank sizes, and reorientation accelerations resulted in reorientation Bond numbers from 1.6 to 23.3.

TABLE I. - LIQUID PROPERTIES AT 20° C

Liquid	Surface tension, σ		Density, ρ	Viscosity, η, cP	Specific surface tension, β, cm^3/sec^2
	dynes/cm	N/cm	$gram/cm^3$		
Ethanol, anhydrous	22.3	22.3×10^{-5}	0.78	1.2	28.3
Trichlorotrifluoroethane	18.6	18.6	1.58	.7	11.8

SYMBOLS

a_R reorientation acceleration, cm/sec^2

Bo_R reorientation Bond number, $Bo_R = a_R(R^2/\beta)$

g acceleration due to gravity, 980 cm/sec^2

R tank radius, cm

r position of collected liquid volume, measured from center of sphere (fig. 2), cm

t time, measured from start of drop test, sec

β specific surface tension, σ/ρ, cm^3/sec^2

η viscosity, cP

ρ density, $gram/cm^3$

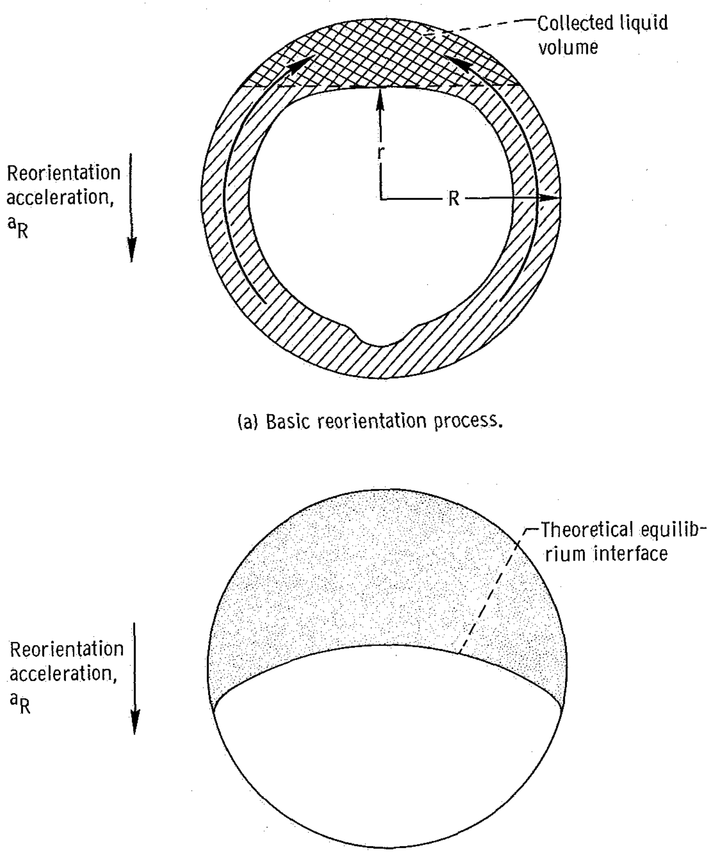
σ surface tension, dynes/cm (N/cm)

RESULTS

General Description of Liquid Reorientation in Spheres

A schematic illustrating the reorientation or collection process is shown in figure 2. The reorientation acceleration a_R causes the liquid to flow from the "bottom" of the tank and to collect at the "top" of the tank. The arrows in figure 2(a) indicate the liquid flow direction during reorientation. In this report, the "collected liquid volume" is defined by the cross-hatched liquid segment. The distance r, measured from the center of the sphere along the acceleration axis, locates this collected liquid volume and provides a quantitative basis for describing the reorientation process.

The position of the liquid after it is completely collected is shown in figure 2(b). The theoretical equilibrium configuration of the interface can be obtained from analytic curves presented by Satterlee in reference 5. For a given contact angle, the theoretical equilibrium interface configuration is completely determined by the percent liquid volume and the reorientation Bond number. The total time required to reorient, or collect, the liquid is the time between the start of the reorientation thrust and the time at which the theoretical equilibrium interface is reached. In this study, with the available range of reorientation Bond numbers and total environmental test time of 2.2 seconds, the equilibrium interface was never observed. The interface passed the equilibrium position and generally oscillated in an axisymmetric mode about this position during the remainder of the test. Under certain conditions, liquid rebound or geysering was observed similar to those cases reported in reference 4. The geyser was essentially a column of liquid growing out of the collecting interface and progressing along the thrust axis in the direction of the acceleration. The geyser may have been the result of unstable interface oscillations. Because of the interface oscillations and geyser phenomena, total collection times were not obtained. However, certain trends in the collection process were noted and the following presentations of representative data may be useful in estimating collection times.



(a) Basic reorientation process.

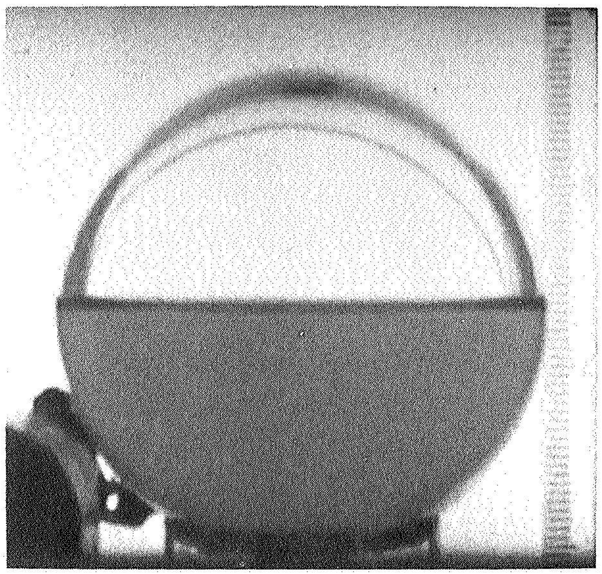
(b) Final collected position.

Figure 2. - Schematic of reorientation in spherical tanks.

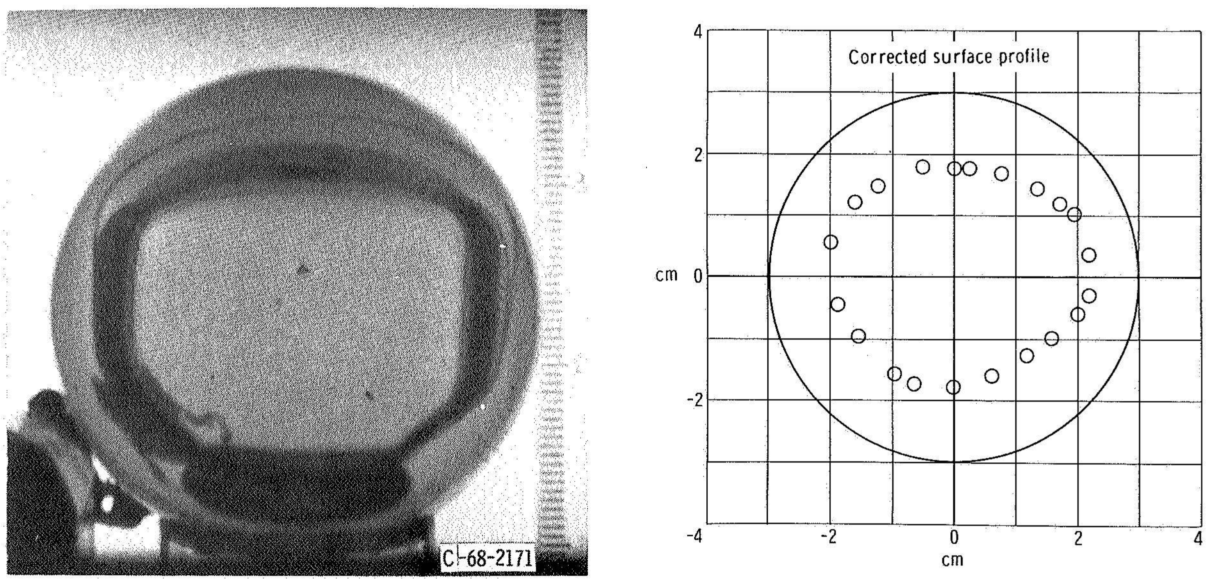
Spherical Interface Initial Condition

One initial condition investigated was that of thrusting, or collecting, from a spherical interface (i.e., the configuration in a zero-Bond-number environment). For these tests, the thruster was fired after the spherical interface had formed. The following data were representative cases of reorientation from this initial interface shape.

Reorientation Bond number of 3.1. - Photographs and corresponding corrected surface profiles at selected times during the reorientation are presented in figure 3. The configuration in the sphere with a liquid volume of 50 percent is shown in figure 3(a) prior to the test drop. The zero-Bond-number configuration was reached approximately 1.3 seconds after entry into weightlessness and is shown in figure 3(b). The interface configuration was nearly spherical in shape and the motion caused by the formation process was essentially damped out. At this time, a reorientation acceleration of 9.8 centimeters per second per second was applied to the system resulting in a reorientation Bond

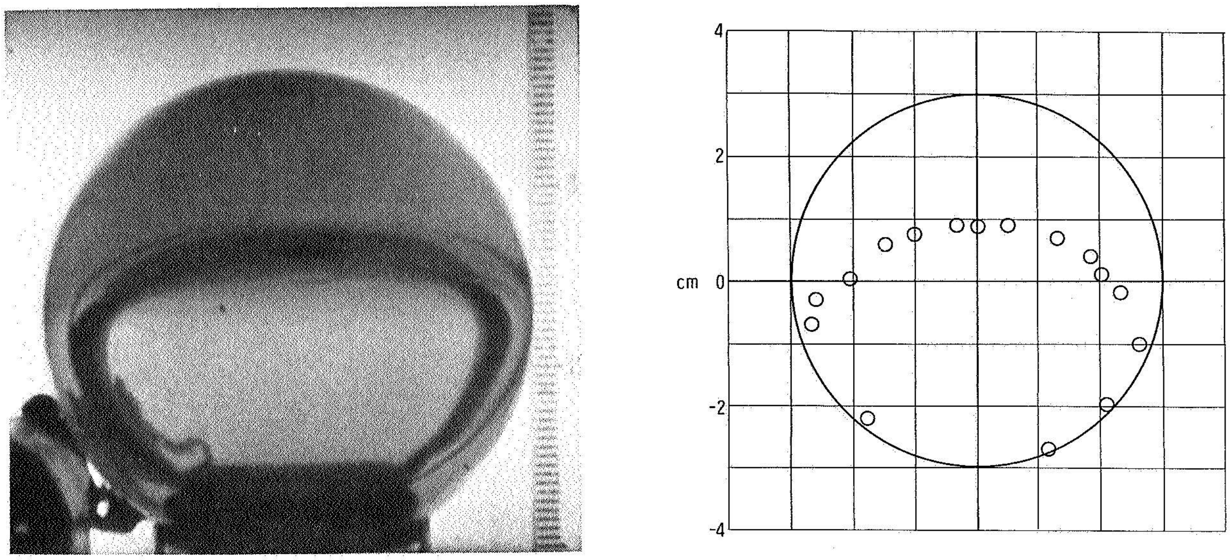


(a) Interface configuration prior to test. Time, 0 second.

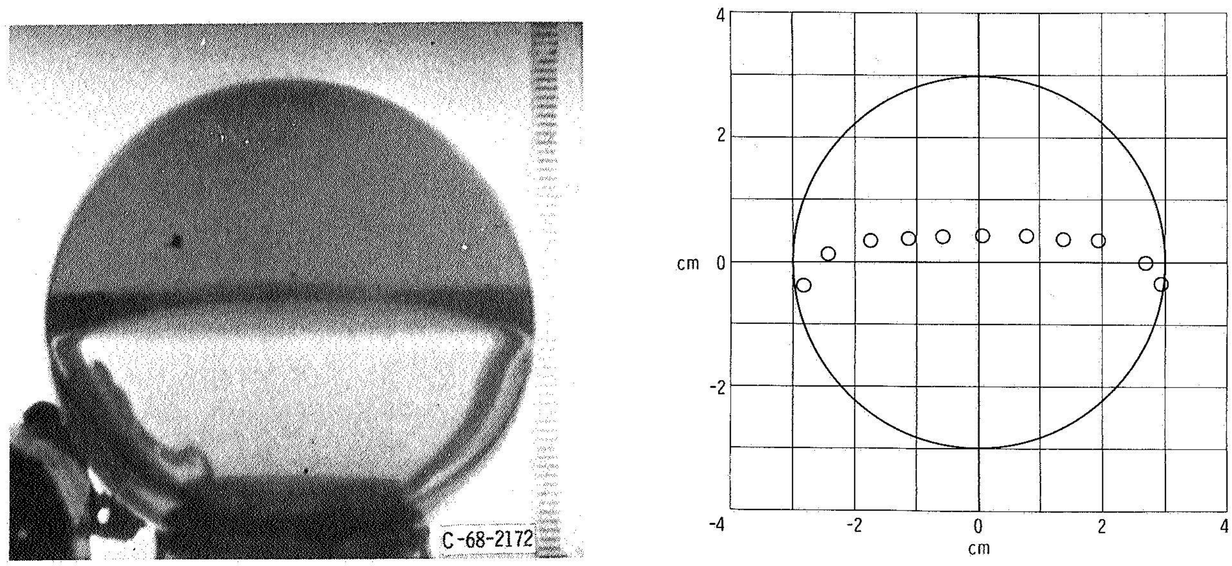


(b) Initiation of thrust. Time, 1.3 seconds.

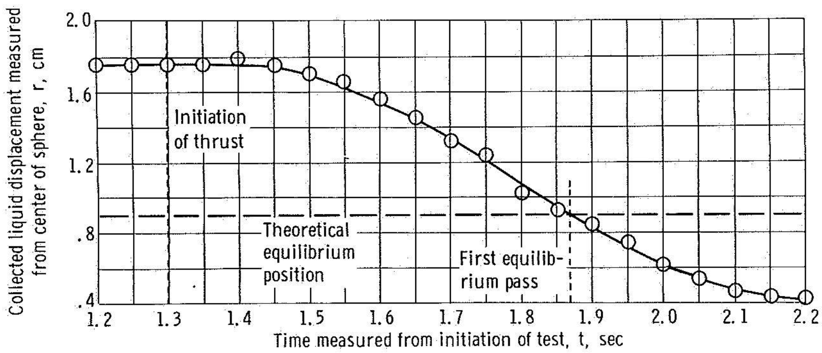
Figure 3. - Collecting from a spherical interface configuration. Reorientation Bond number, 3.1; reorientation acceleration, 9.8 centimeters per second squared; tank radius, 3 centimeters; test liquid, ethanol; liquid volume, 50 percent.



(c) Approximate equilibrium pass. Time, 1.88 seconds.



(d) Termination of test. Time, 2.22 seconds.



(e) Time history of reorientation during test.

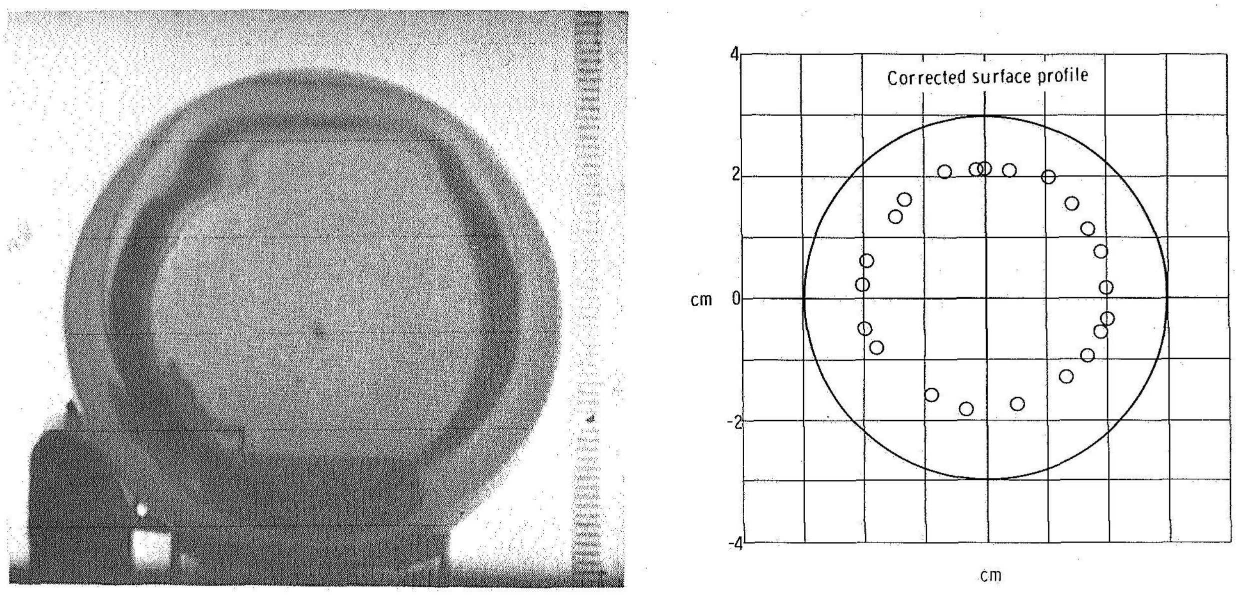
Figure 3. - Concluded.

number of 3. 1. The liquid began to collect in the top of the sphere. The position of the equilibrium interface along the acceleration axis was first reached approximately 0. 58 second after the start of the reorientation acceleration (fig. 3(c)). However, a very thin layer of liquid still remained along the tank wall, and the interface continued to progress downward. Near the end of the test (fig. 3(d)), most of the liquid was collected and the interface was essentially flat. The time history of the collected liquid volume, measured by the distance r, is given in figure 3(e). Near the end of the test, the displacement rate (the slope of the curve in fig. 3(e)) was nearly zero since most of the liquid had been collected. If more test time had been available, the interface would have proceeded to oscillate symmetrically along the acceleration axis and tank wall until damping caused the equilibrium interface to be reached.

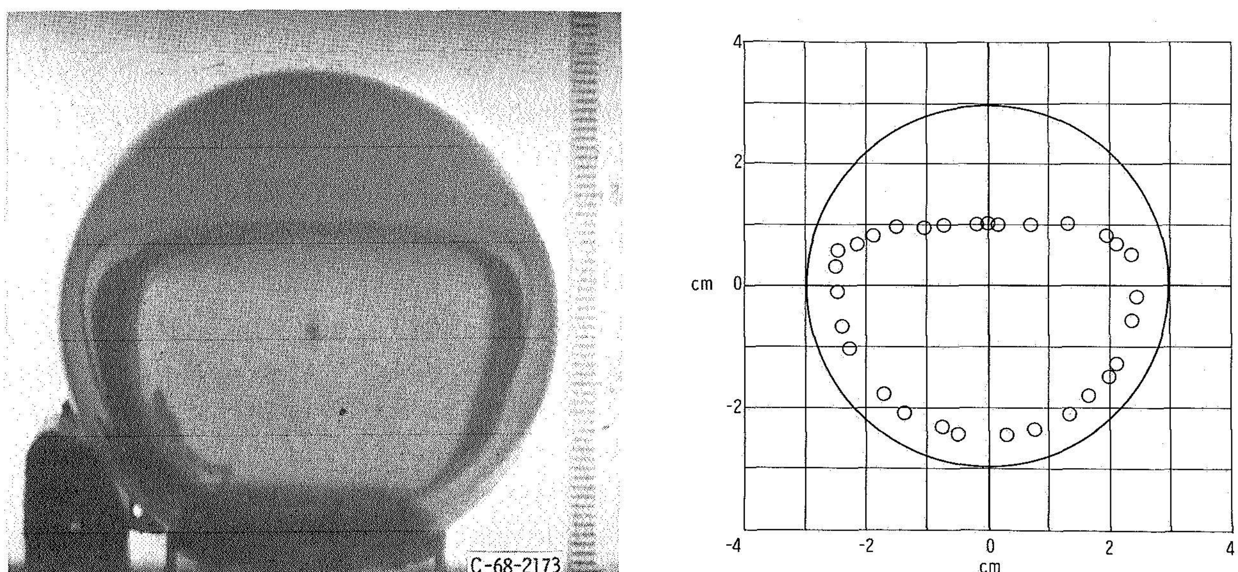
The reorientation process was axisymmetric at the reorientation Bond number of 3. 1. Approximately 0. 6 second was required for the interface to reach its first equilibrium pass.

Reorientation Bond number of 6. 2. - In figure 4, the representative photographs and corrected surface profiles are shown for the case of collecting from an initially spherical interface configuration with a reorientation Bond number of 6. 2. Figure 4(a) shows the interface configuration at the initiation of thrust. The percent liquid volume was again 50 percent. About 1. 7 seconds after the initiation of the test, the collected liquid interface began to show the initial stage of an apparent geyser. (The term "apparent geyser" is used herein to denote a geyser whose height is relatively small and which may be a symmetric oscillation of the collecting interface.) In figure 4(c), the equilibrium position was reached and the geyser was approaching a maximum height relative to the collecting interface; at 2. 10 seconds, the geyser was observed to reach its maximum height. (The surface profile of the geyser given in fig. 4(c) is only approximate since refraction occurred through a thin layer of liquid.) The collected liquid displacement-time history of this process is shown in figure 4(d). The displacement rate decreased while the geyser was forming. This indicated that most of the collected liquid was contained in the geyser. The equilibrium position was initially passed approximately 0. 75 second after initiation of thrust. Despite the apparent geyser, most of the liquid was collected at the end of the test. This reorientation process was axisymmetric and displayed an apparent geyser at the reorientation Bond number of 6. 2.

Reorientation Bond number of 9. 7. - In figure 5, representative profiles are presented for the case of collecting with a reorientation Bond number of 9. 7. Again, the first figures indicate the interface configuration at the initiation of thrust. In figure 5(b), the configuration during the collection period is shown. The initial growth of an apparent geyser was observed at about 1. 60 seconds. In figure 5(d), the geyser continued to grow. However, the geyser receded back into the collected liquid as the equilibrium position was passed (fig. 5(e)). This pass through equilibrium along with a time history of the

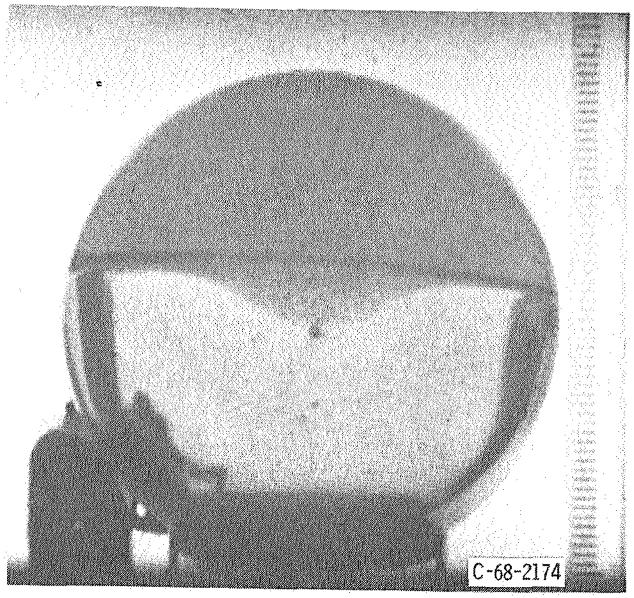


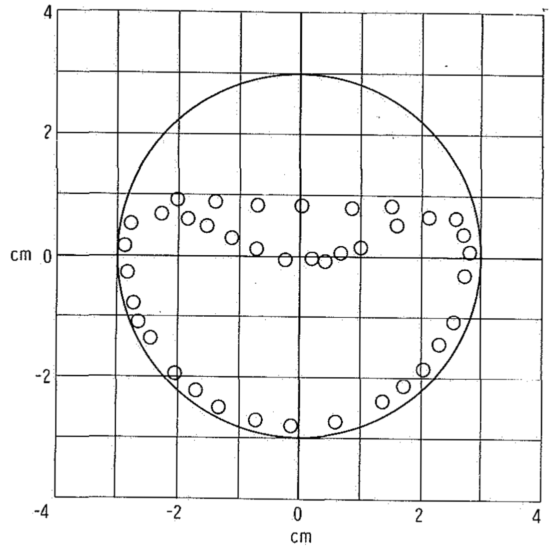
(a) Initiation of thrust. Time, 1.3 seconds.



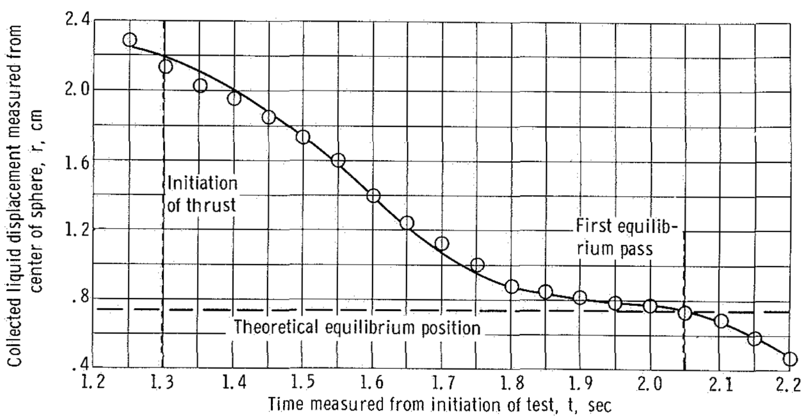
(b) Interface shape prior to start of geyser growth. Time, 1.73 seconds.

Figure 4. - Collecting from a spherical interface configuration. Reorientation Bond number, 6.2; reorientation acceleration, 19.6 centimeters per second squared; tank radius, 3 centimeters; test liquid, ethanol; liquid volume, 50 percent.





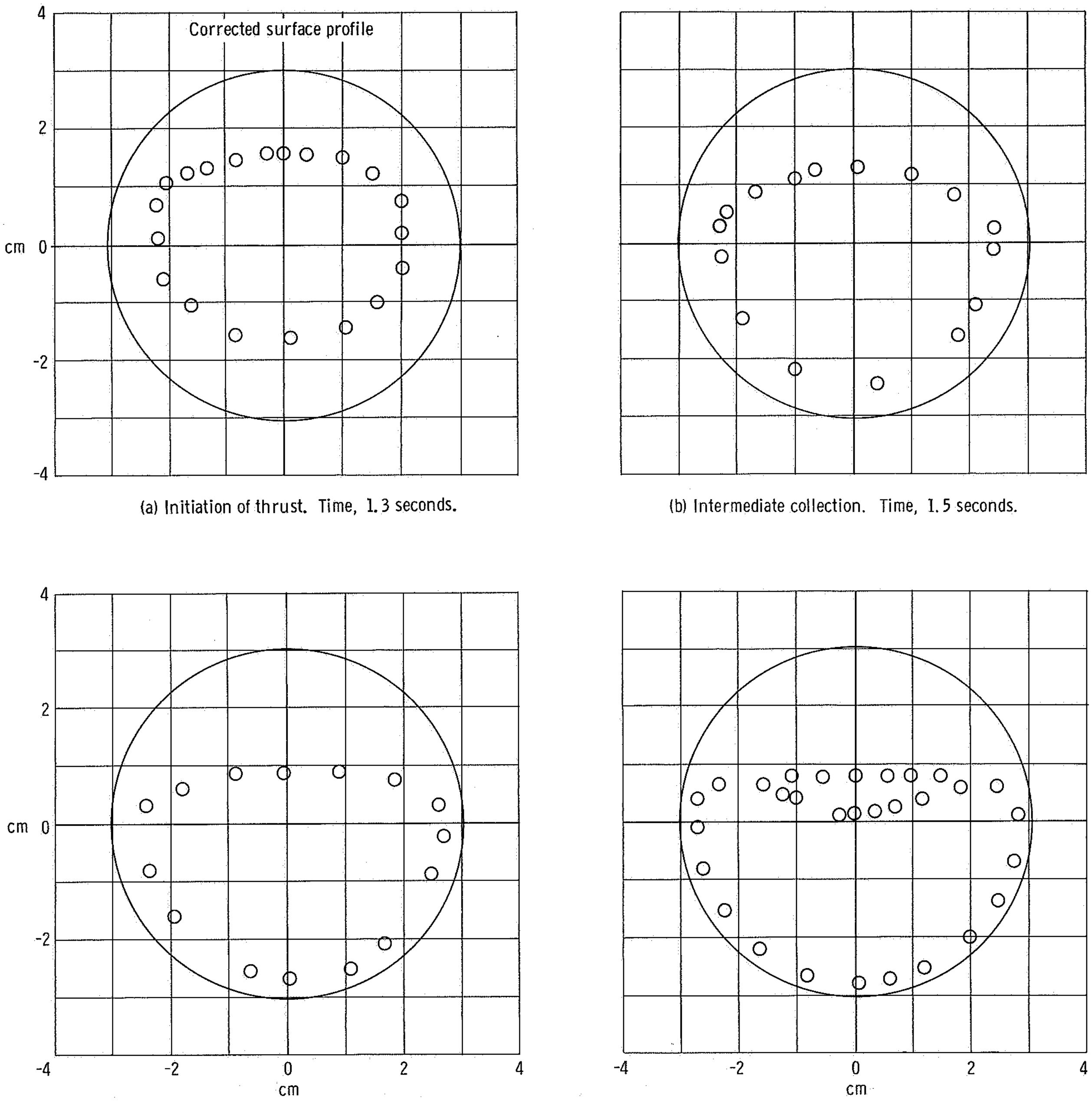
(c) Equilibrium pass; geyser height near maximum. Time, 2.05 seconds.



(d) Time history of reorientation during test.

Figure 4. - Concluded.

collected interface is given in figure 5(f). From these results, it can be seen that the equilibrium position was reached approximately 0.8 second after the initiation of thrust, with the interface continuing to progress downward. The interface remained essentially at a constant distance from the center of the sphere during the interval between 1.60 and 2.00 seconds. This was attributed to the loss in collected liquid volume during geyser formation. When the geyser receded, the rate of collection increased. This reorientation process was axisymmetric and exhibited the formation of an apparent geyser at the reorientation Bond number of 9.7.



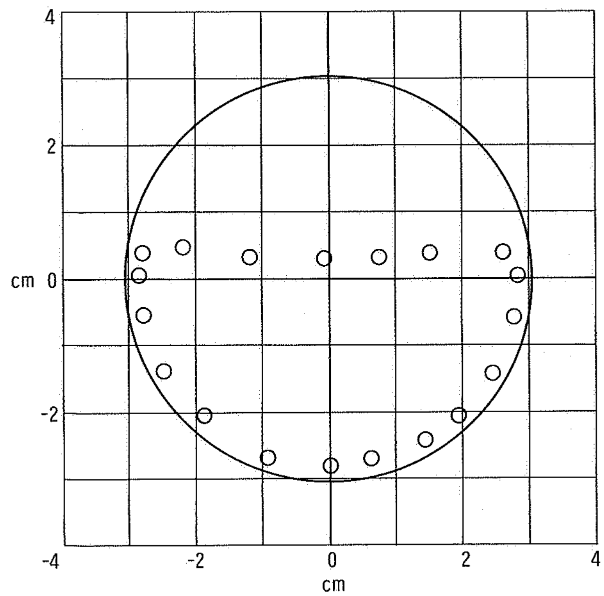
(a) Initiation of thrust. Time, 1.3 seconds.

(b) Intermediate collection. Time, 1.5 seconds.

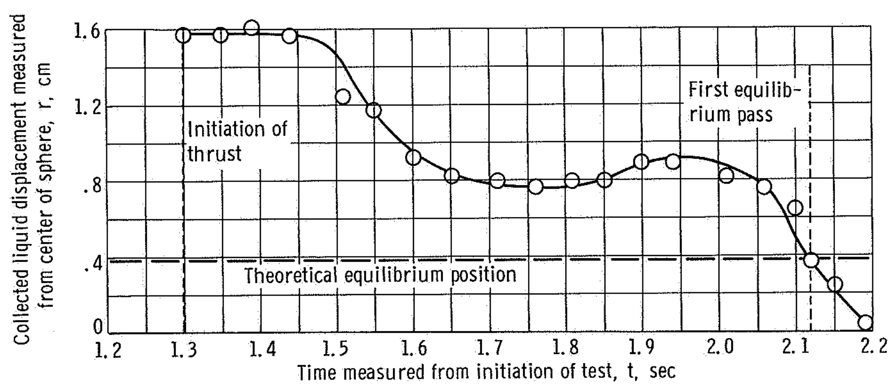
(c) Interface shape prior to start of geyser growth. Time, 1.6 seconds.

(d) Geyser growth continues. Time, 1.8 seconds.

Figure 5. - Collecting from a spherical interface configuration. Reorientation Bond number, 9.7; reorientation acceleration, 29.4 centimeters per second squared; tank radius, 3.06 centimeters; test liquid, ethanol; liquid volume, 50 percent.



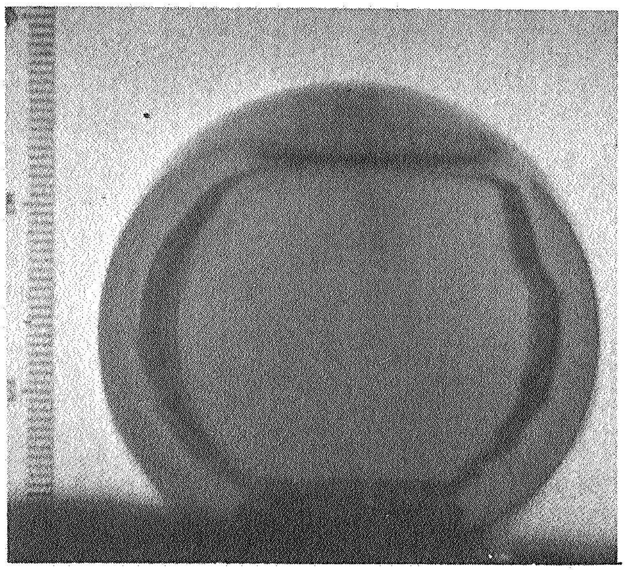
(e) Approximate equilibrium pass; geyser has receded. Time, 2.11 seconds.



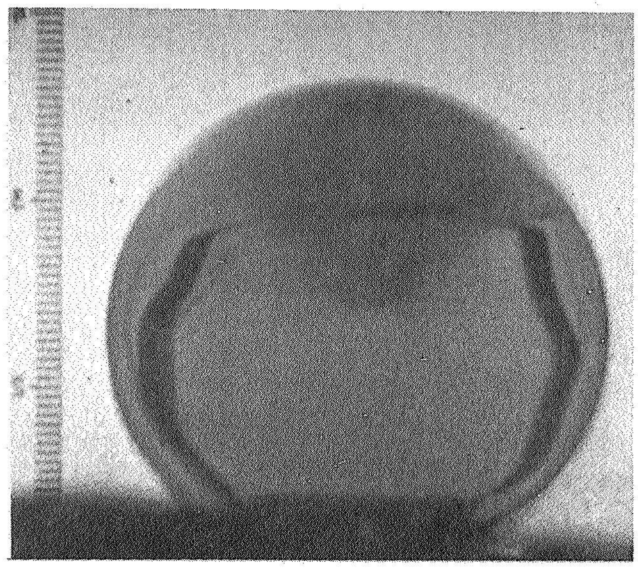
(f) Time history of reorientation during test.

Figure 5. - Concluded.

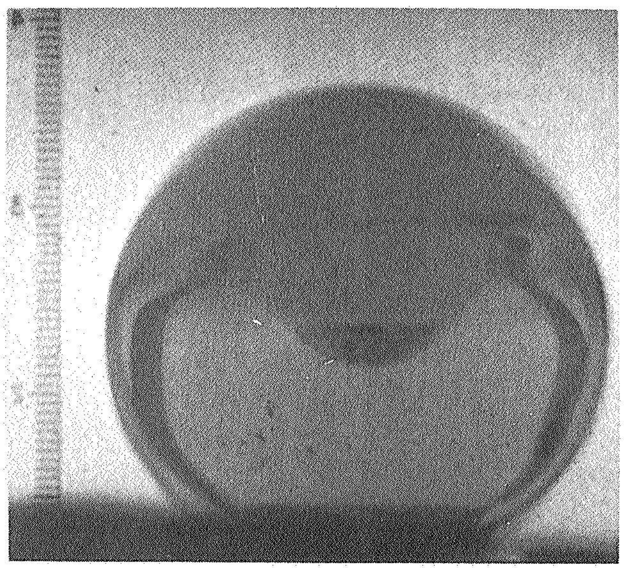
Reorientation Bond number of 23. 3. - A relatively high Bond number of 23. 3 was obtained in a 3. 06-centimeter-radius sphere with trichlorotrifluoroethane as the test liquid. The sequence of events is shown in figure 6. The liquid volume was again 50 percent. Figure 6(a) shows the interface configuration at the initiation of thrust. The relatively large geyser that appeared and grew rapidly is shown in figures 6(b) and (c). The configuration of the liquid-vapor interface prior to the termination of the drop at 2. 20 seconds is shown in figure 6(d). This reorientation process was axisymmetric and a large geyser



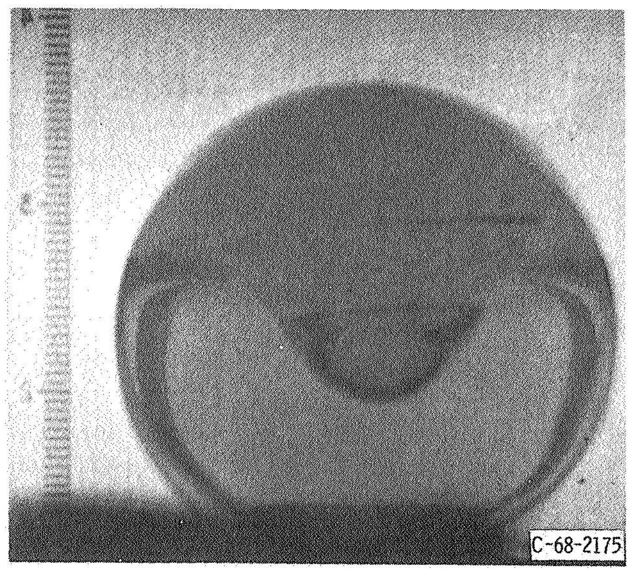
(a) Initiation of thrust. Time, 1.75 seconds.



(b) Geyser appears. Time, 2.07 seconds.

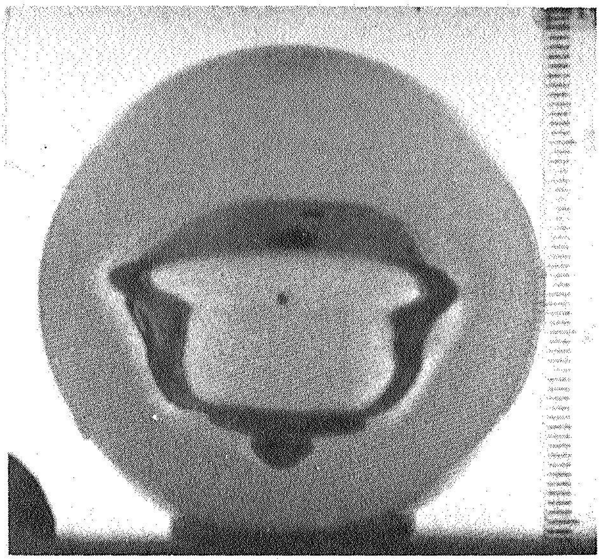


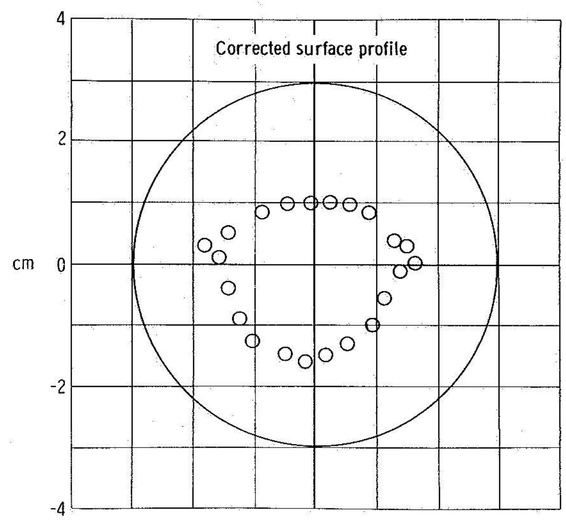
(c) Geyser grows rapidly. Time, 2.17 seconds.



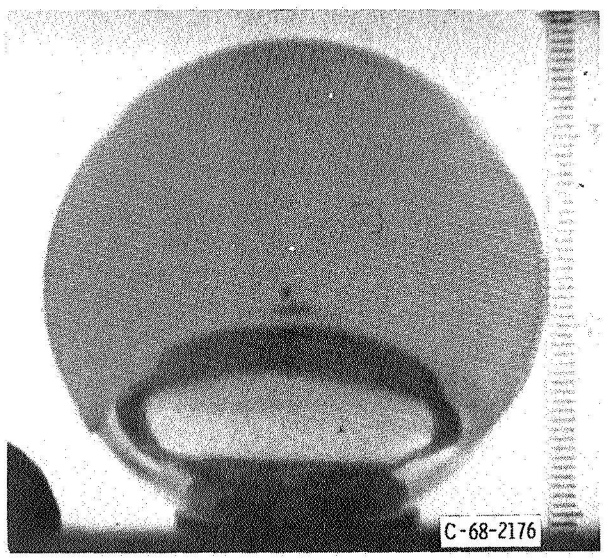
(d) Termination of test; geyser still growing. Time, 2.2 seconds.

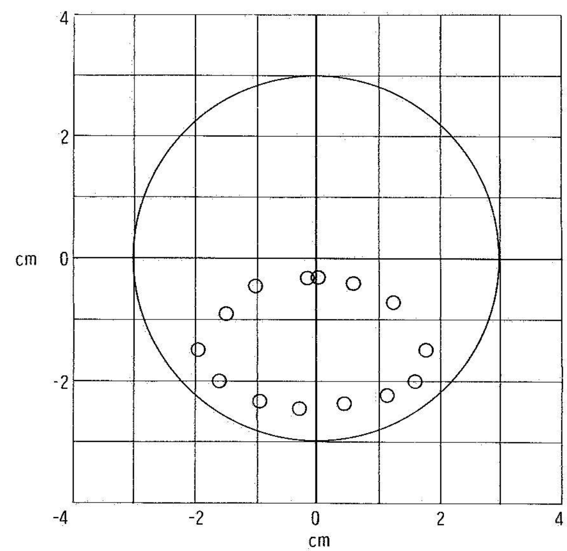
Figure 6. - Collecting from a spherical interface configuration. Reorientation Bond number, 23.3; reorientation acceleration, 29.4 centimeters per second squared; tank radius, 3.06 centimeters; test liquid, trichlorotrifluoroethane; liquid volume, 50 percent.





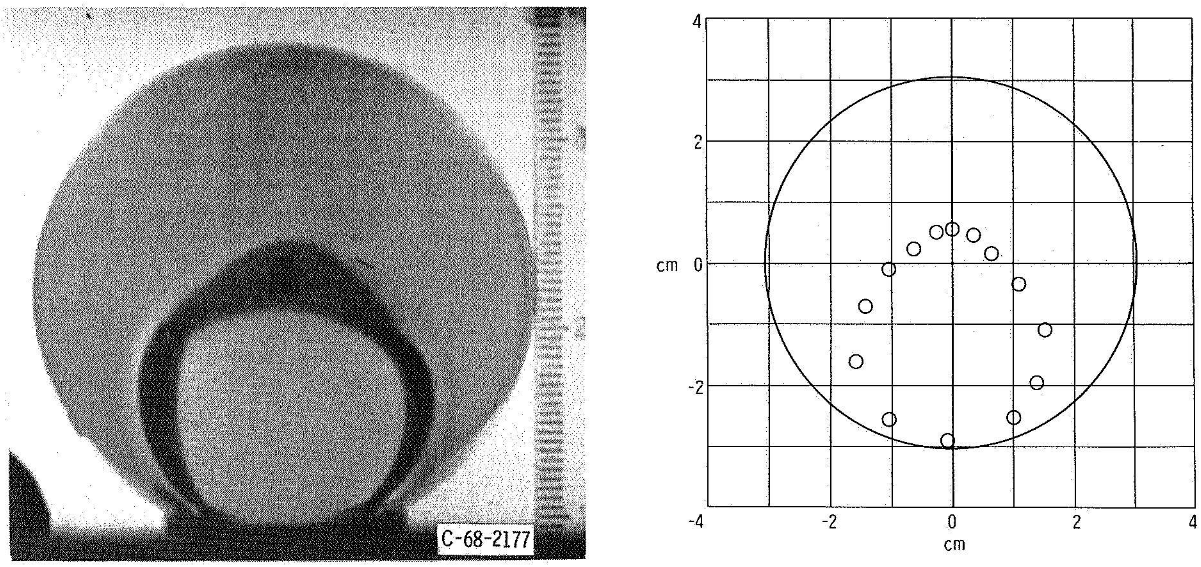
(a) Initiation of thrust. Time, 0.8 second.



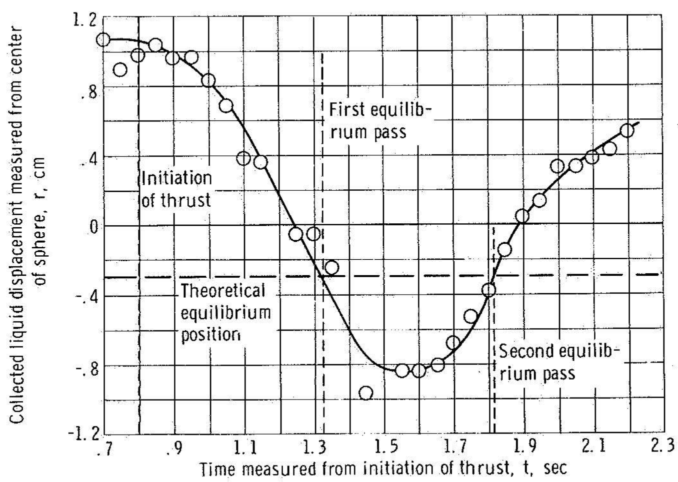


(b) Approximate equilibrium pass. Time, 1.33 seconds.

Figure 7. - Collecting from a spherical interface configuration. Reorientation Bond number, 3.2; reorientation acceleration, 9.8 centimeters per second squared; tank radius, 3.06 centimeters; test liquid, ethanol; liquid volume, 80 percent.



(c) Termination of test. Time, 2.21 seconds.



(d) Time history of reorientation during test.

Figure 7. - Concluded.

was formed which was still growing at the end of the test at a reorientation Bond number of 23.3.

Effect of liquid volume. - Data over a range of liquid volumes from 40 to 80 percent were obtained. The data for a representative test with a large liquid volume are given in figure 7. For this test, an 80-percent liquid volume was used. The reorientation Bond number was 3.2. Initiation of thrust is shown in figure 7(a). At this time, the vapor-bubble was extremely distorted because of radial oscillations characteristic of the interface formation process for large liquid volumes. The oscillating vapor bubble moved downward, first passing the equilibrium position 0.53 second after the acceleration was applied. The vapor bubble passed through equilibrium for a second time and the interface was still oscillating with very large amplitude during the remainder of the test. It should also be noted that in the available test time, some liquid was always observed along the tank wall (in particular, at the bottom of the sphere).

This reorientation process was axisymmetric and exhibited no geyser at the reorientation Bond number of 3.2. The large percentage of liquid resulted in comparatively small vapor-bubble motion during the reorientation. The large liquid volume and low reorientation Bond number resulted in large amplitude oscillations about the theoretical equilibrium position. Similar results were observed for tests with liquid volumes of 70 percent.

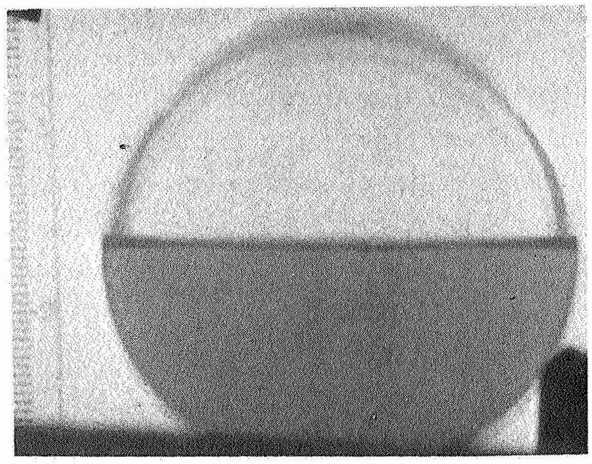
In general, the behavior at liquid volumes of 40 percent was similar to that observed at 50 percent. No data were obtained at liquid volumes less than 40 percent because of the excessive time required to form the initial zero-Bond-number configuration.

Flat Interface Initial Condition

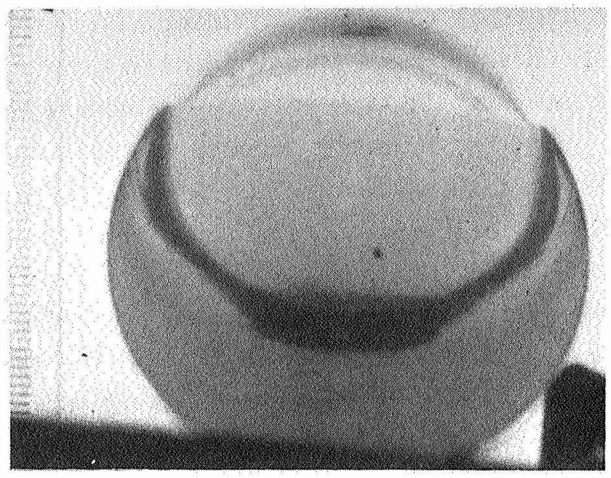
A second initial condition investigated was that of collecting from a normal-gravity, essentially flat interface. For these tests, the thruster was fired before the experiment package was released. This resulted in an instantaneous transition from a high Bond number to a low reorientation Bond number when the package was released. The initial, 1-g Bond numbers ranged from 150 to about 800. The following data were representative cases of reorientation from this initial interface shape.

Reorientation Bond number of 3.2. - The sequence of events is shown in figure 8 for reorientation from an initially flat interface. The reorientation Bond number was 3.2. The liquid, tank radius, and percent liquid volume were identical to the test previously described in figure 3. The only difference between these tests was the initial interface configuration.

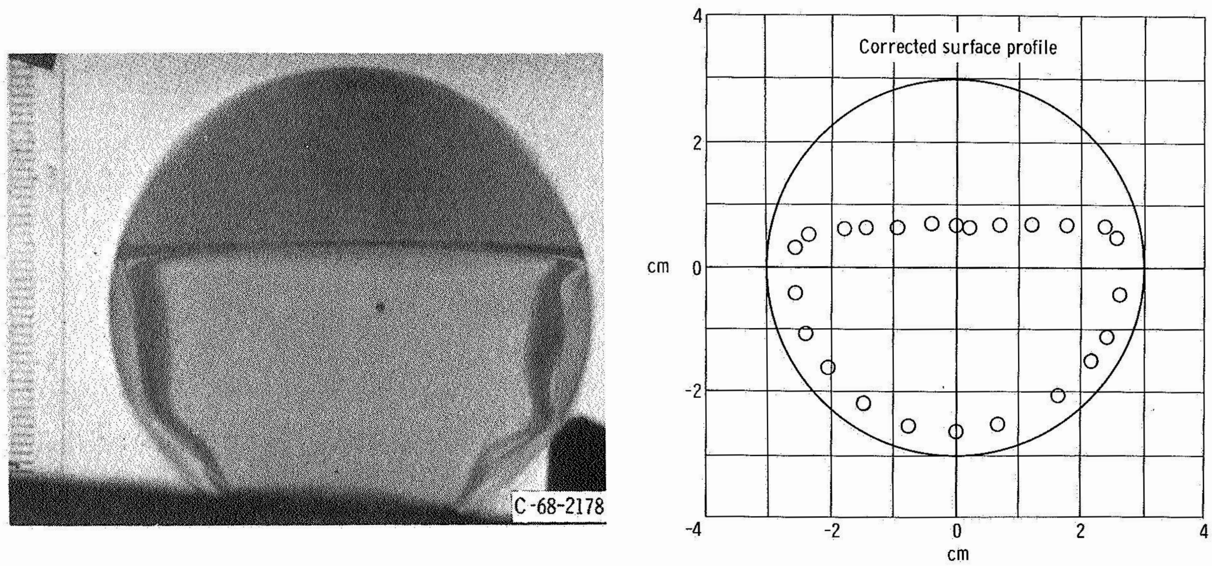
The liquid configuration at the start of the test is shown in figure 8(a). In figure 8(b), the liquid accelerated toward the top portion of the sphere and the vapor moved toward the bottom of the sphere. The liquid met at the top of the tank, thereby enclosing the vapor. In figure 8(c), 1.35 seconds after the start of thrust, most of the liquid was collected and the interface was essentially flat. Toward the end of the test, the interface began to regain its curved shape under the action of the low reorientation Bond number. A time history of the motion of the interface along the acceleration axis is given in figure 8(e). The first point on the graph was the approximate time at which the liquid met at the top of the tank.



(a) Initiation of thrust. Time, 0 second.

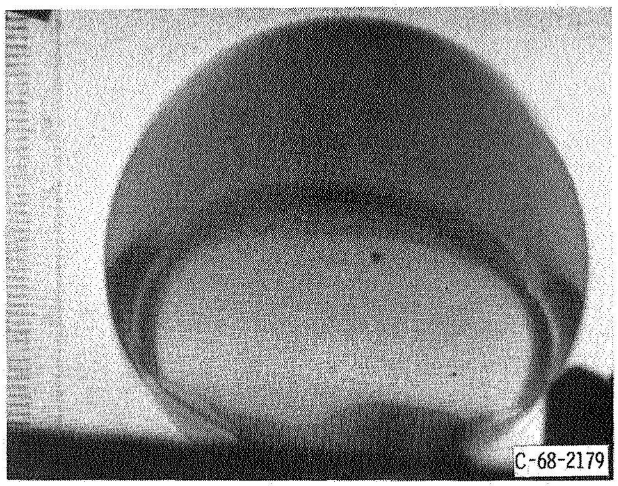


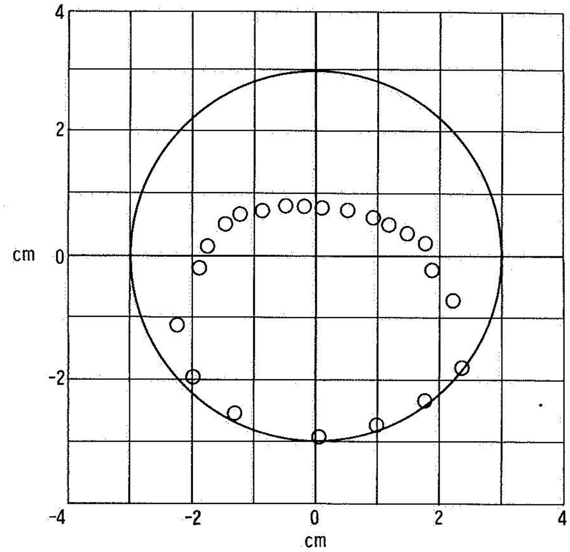
(b) Liquid accelerates up container walls. Time, 0.35 second.



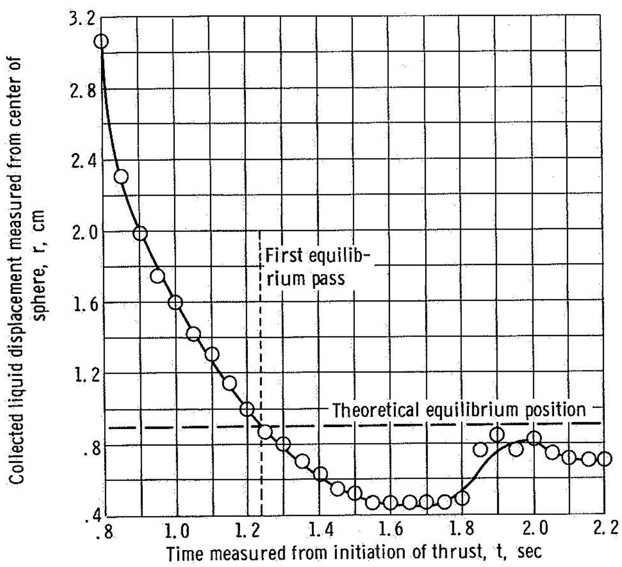
(c) Intermediate collection. Time, 1.35 seconds.

Figure 8. - Collecting from an initially flat interface configuration. Reorientation Bond number, 3.2; reorientation acceleration, 9.8 centimeters per second squared; tank radius, 3.06 centimeters; test liquid, ethanol; liquid volume, 50 percent.





(d) Configuration prior to termination of test. Time, 2.23 seconds.



(e) Time history of reorientation during test.

Figure 8. - Concluded.

Reorientation Bond number of 6. 5. - A time history of the collected liquid volume for this representative test is shown in figure 9. At the reorientation Bond number of 6. 5, approximately 1. 45 seconds was required for the interface to pass through its theoretical equilibrium position. An apparent geyser similar to the one shown in figure 4 was present. The reorientation process was again axisymmetric.

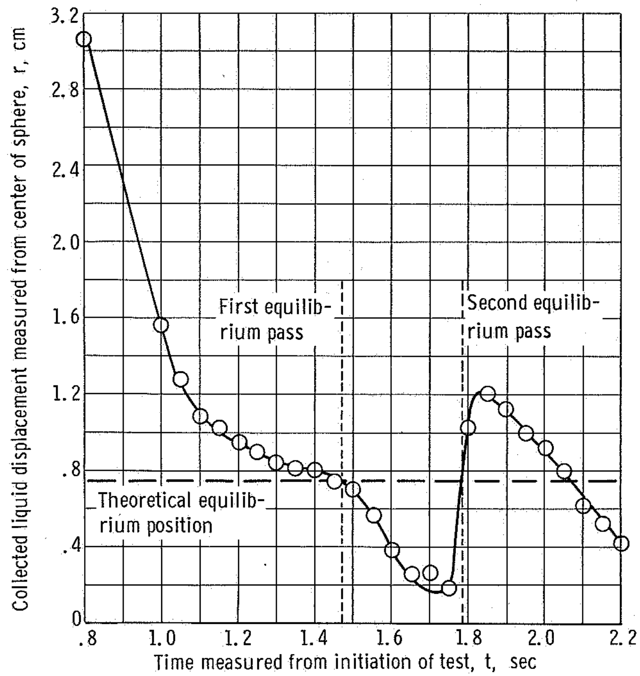
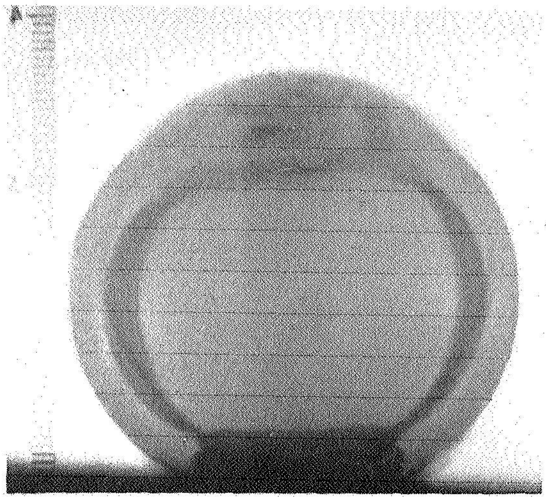


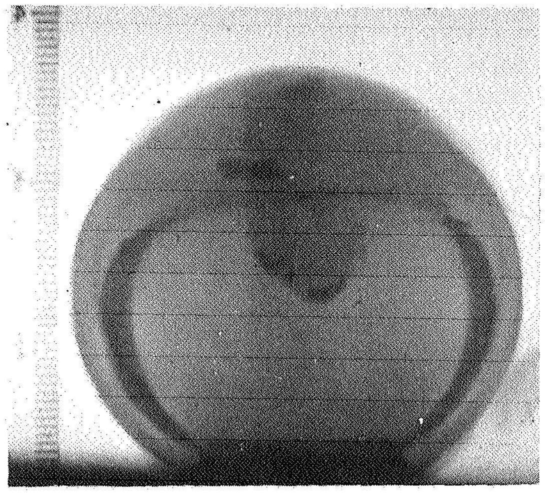
Figure 9. - Time history of reorientation during test. Reorientation Bond number, 6. 5; reorientation acceleration, 19. 6 centimeters per second squared; tank radius, 3 centimeters; test liquid, ethanol; liquid volume, 50 percent.

Reorientation Bond number of 23. 3. - A reorientation Bond number of 23. 3 was obtained with a 3. 06-centimeter-radius sphere with trichlorotrifluoroethane as the test liquid. The sequence of events is shown in figure 10. The reorientation process was similar to those shown previously. However, a large geyser was produced which nearly reached the opposite portion of the sphere (fig. 10(d)). Toward the end of the test, the geyser receded into the collected liquid, generating a return flow along the walls of the tank. The return flow resulted in the turbulence seen in figures 10(e) and (f).

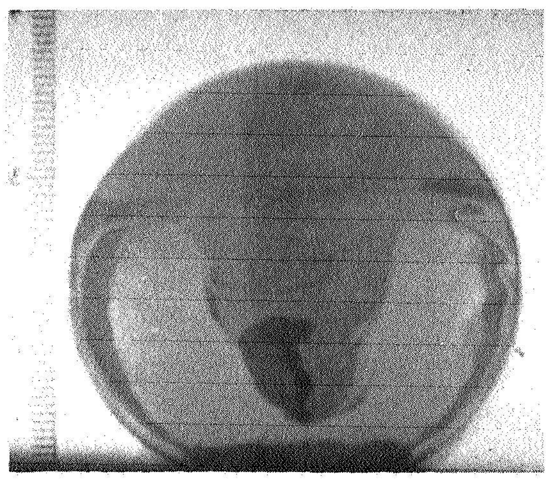
Effect of liquid volume. - For this initial condition, data over a range of liquid volumes from 30 to 80 percent were obtained. A representative test with a 70-percent liquid volume is shown in figure 11. The reorientation Bond number was 1. 6. The liquid accelerated up the container wall and enclosed the vapor at approximately 0. 35 second.



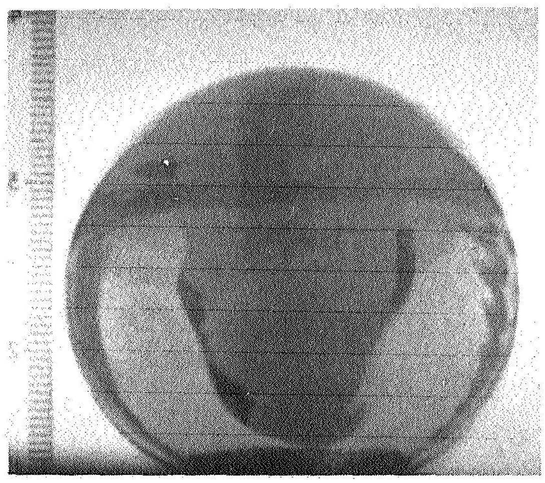
(a) Vapor entirely enclosed. Time, 0.98 second.



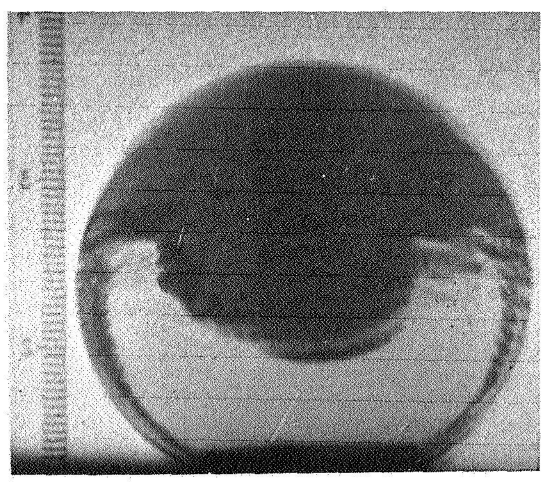
(b) Geyser begins to grow. Time, 1.12 seconds.



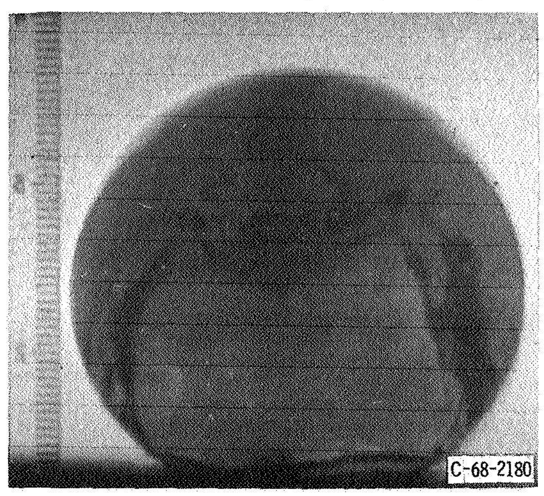
(c) Geyser grows rapidly. Time, 1.39 seconds.



(d) Geyser reaches maximum height. Time, 1.58 seconds.

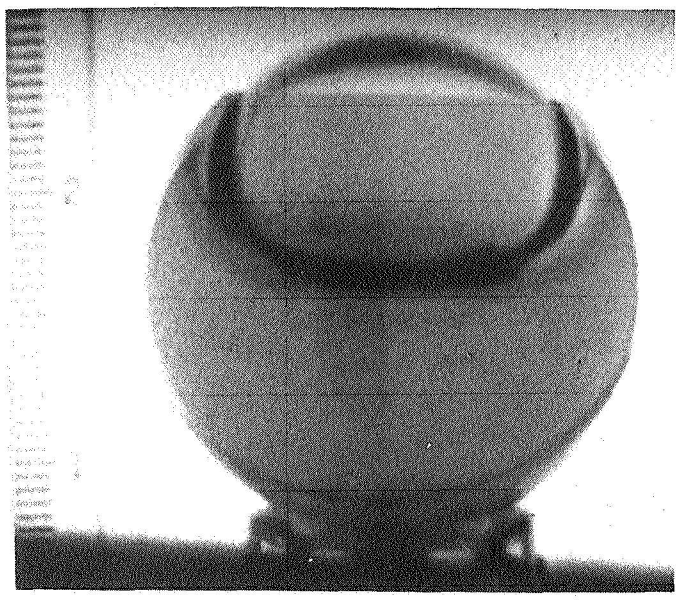


(e) Geyser is receding. Time, 1.93 seconds.

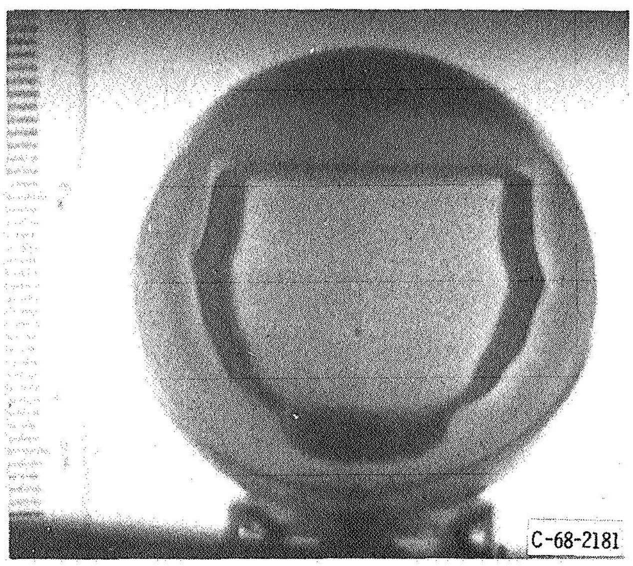


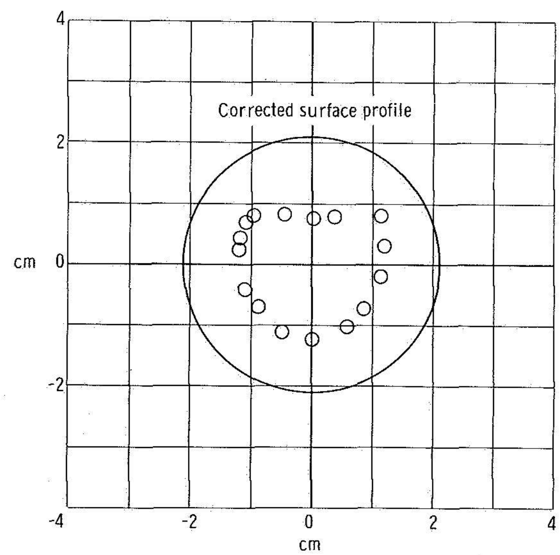
(f) Interface begins to oscillate. Time, 2.23 seconds.

Figure 10. - Collecting from an initially flat interface configuration. Reorientation Bond number, 23.3; reorientation acceleration, 29.4 centimeters per second squared; tank radius, 3.06 centimeters; test liquid, trichlorotrifluoroethane; liquid volume, 50 percent.



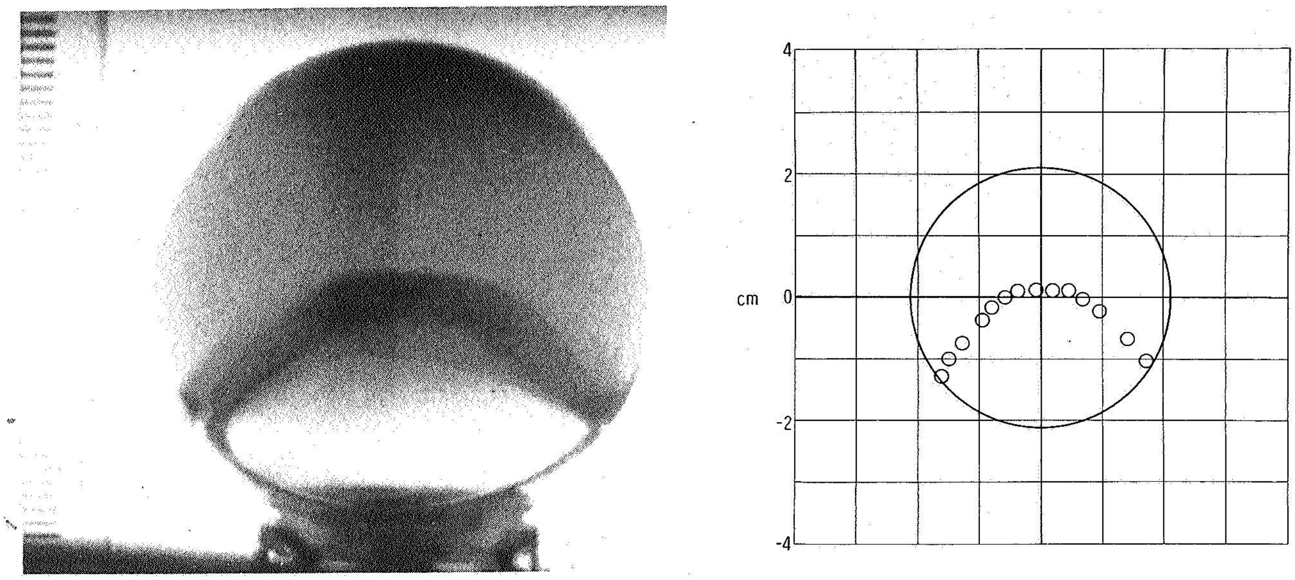
(a) Liquid accelerates up container walls. Time, 0.15 second.



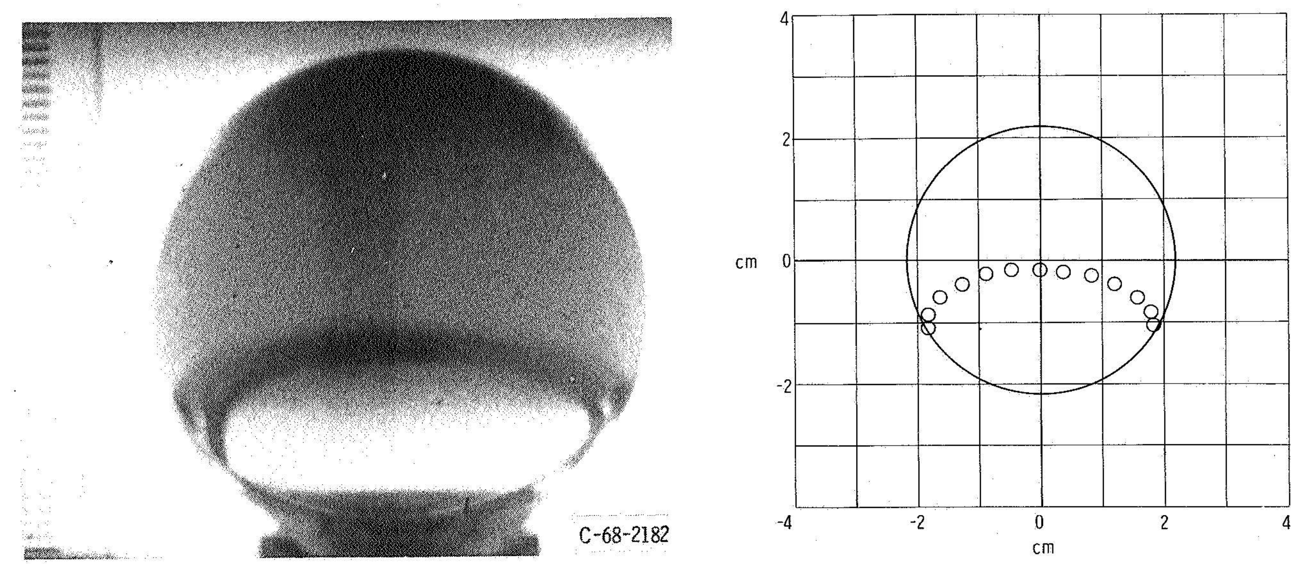


(b) Vapor bubble enclosed. Time, 0.48 second.

Figure 11. - Collecting from an initially flat interface configuration. Reorientation Bond number, 1.6; reorientation acceleration, 9.8 centimeters per second squared; tank radius, 2.12 centimeters; test liquid, ethanol; liquid volume, 70 percent.

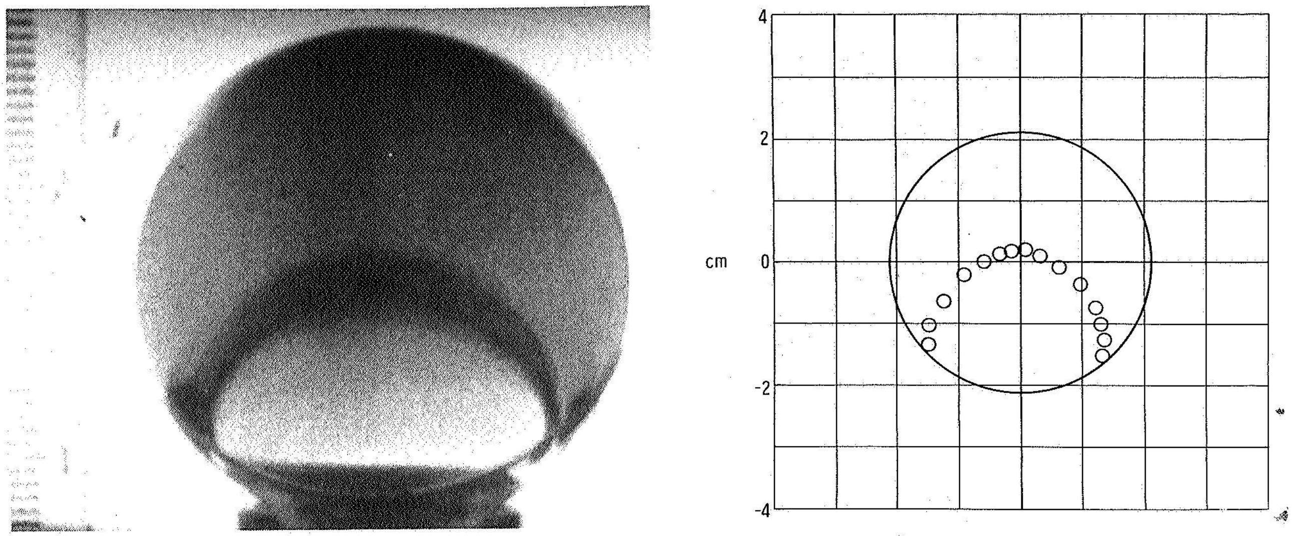


(c) First equilibrium pass. Time, 1.09 seconds.

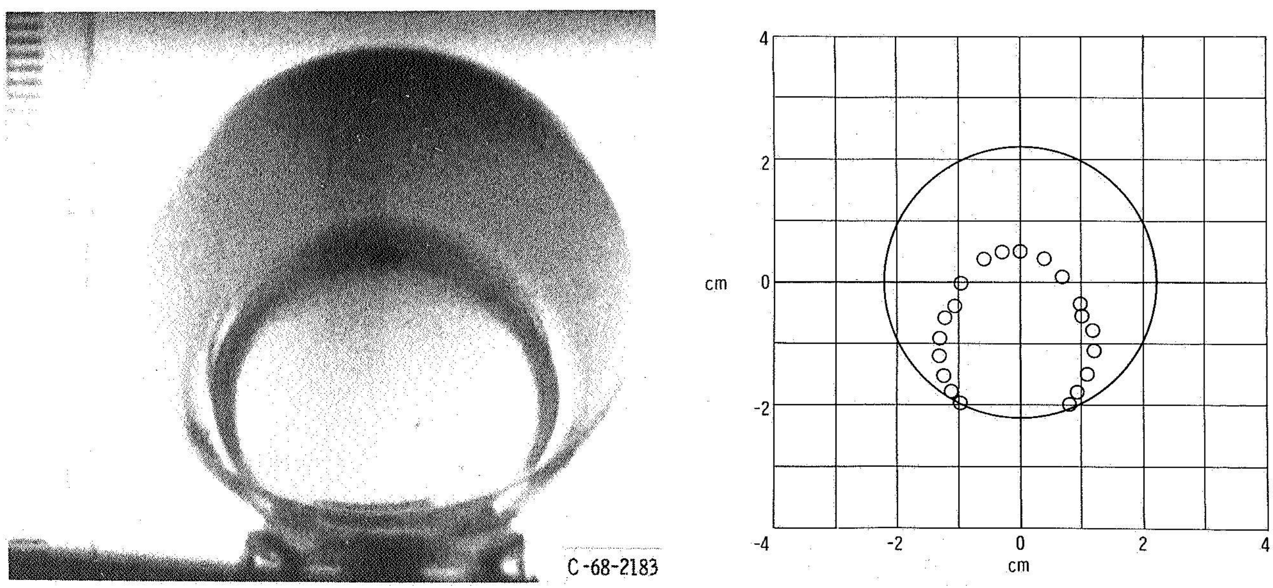


(d) Interface reaches first low pass. Time, 1.2 seconds.

Figure 11. - Continued.

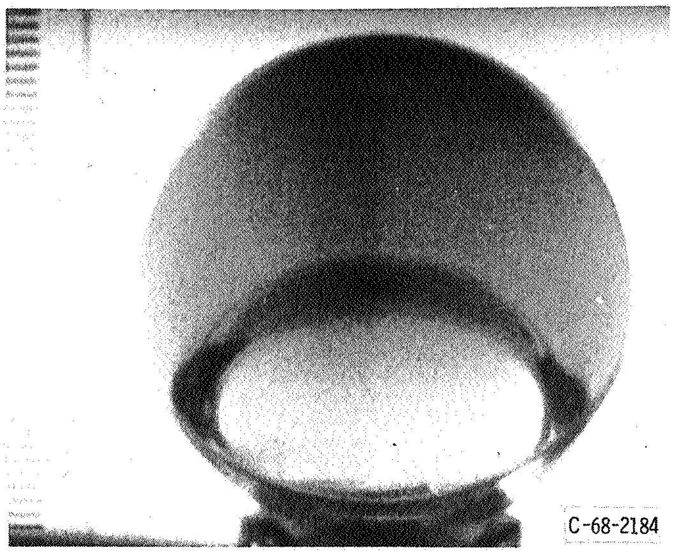


(e) Second equilibrium pass. Time, 1.4 seconds.

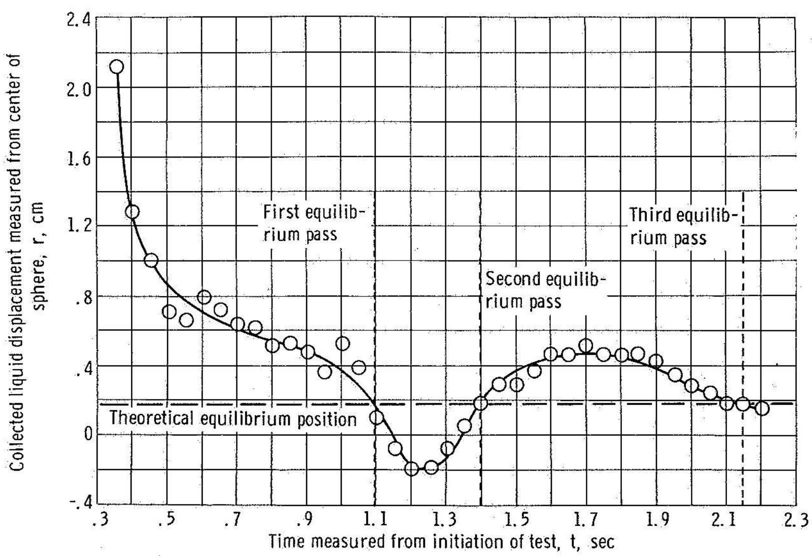


(f) Interface reaches first high pass and oscillations continue. Time, 1.75 seconds.

Figure 11. - Continued.



(g) Third equilibrium pass. Time, 2.1 seconds.



(h) Time history of reorientation during test.

Figure 11. - Concluded.

The initial collection rate was quite large. The vapor bubble moved down, thereby forming the collected liquid-vapor interface. Symmetric mode oscillations about the equilibrium position are clearly illustrated by the remaining photographs of this figure. The reorientation process was axisymmetric and no geyser was formed.

Liquid fillings as small as 30 percent showed no essential difference when compared with the representative 50-percent fillings previously shown. No data were obtained for fillings less than 30 percent.

DISCUSSION OF RESULTS

The preceding data illustrated the general aspects of low-Bond-number reorientation observed in this experimental study. The reorientation process in spherical containers displayed the same complex behavior as reported for cylindrical containers (ref. 4).

Qualitative Observations

Symmetry. - The results of this study showed that reorientation in spheres was axisymmetric under both initial interface conditions studied. Even when liquid rebound or geysering occurred, the reorientation flow, including the geyser growth, was always observed to be symmetric about the acceleration axis. Additionally, no significant Taylor-type instabilities were observed during the initial phases of the reorientation. However, this may be the expected situation for reorientation Bond numbers less than 23, the largest used in this study (see studies in ref. 7).

Geyser. - The amount and rate of liquid collection were influenced by geyser occurrence. When geysering occurred, a portion of the collected liquid was contained in the geyser. This may be seen in the time history graphs previously presented (e.g., figs. 4(d) and 5(f)). From the data presented, geysering apparently depends on the magnitude of the reorientation Bond number. When collecting from a spherical interface configuration, for all liquid fillings, no geysers occurred at or below Bond numbers of 3.2; geysers did appear for Bond numbers greater than 6.5. For the case of collecting from an initially flat interface, geysers did not occur for reorientation Bond numbers less than 3.2; geysers did appear for Bond numbers greater than or equal to 4.9. Furthermore, it is apparent from the data that the severity of the geyser depends directly on the reorientation Bond number.

We speculate, however, that geyser occurrence will depend on the liquid flow velocity at the collected interface rather than explicitly on the reorientation Bond number (cf., the correlation in ref. 4 for cylindrical containers). For example, it was observed that the height of the geyser from the collected interface decreased with increasing liquid filling at a given reorientation Bond number. Also, a comparison of figures 6 and 10 shows that the geyser was more severe in the case of collecting from a flat interface. The liquid-flow velocity into the collected region would be higher in the case of collecting from a flat interface because of the added momentum gained by initially accelerating along the container wall. This indicates that flow velocity, which depends on the reorientation acceleration and the distance traveled along the wall of the sphere, is the important parameter in determining geyser occurrence.

Effect of System Variables

Reorientation acceleration. - As might be expected, the amount of liquid collected increased with increasing reorientation acceleration (for otherwise equal variables such as tank radius and liquid volume). For example, a comparison of figures 3(e), 4(d), and 5(f) shows that the initial rates of collection increased as the reorientation acceleration was increased. Also, a comparison of the initial slopes in figures 8(e) and 9 shows the same trend. Total collection time, however, could not be correlated with reorientation acceleration because of the varying collecting rates due to geyser formation.

Percent liquid volume. - The percentage of liquid volume was an important parameter in the reorientation process. As previously noted, the percentage of liquid volume determined the collected equilibrium interface configuration. The liquid volume also determined the reorientation flow pattern. For liquid volumes of 70 percent or greater, reorientation resulted in "small" vapor bubble motion. Liquid volume partly determined geyser formation. Finally, liquid volume partly determined the character of oscillations about the equilibrium position.

Initial conditions. - For the range of reorientation Bond numbers used in this study, the reorientation process was essentially the same for different initial interface configurations. Collecting from an initially spherical interface was qualitatively the same as collecting from an initially flat interface. Of course, in the former case a portion of the liquid was already collected. When collecting from a flat interface, some additional collection time was required for the liquid to initially move along the tank walls. The added momentum of the liquid as it moved up the tank walls resulted in an initially larger collection rate than for an identical test with an initially spherical interface shape. This was seen, for example, in figures 3(e) and 8(e). For reorientation Bond numbers less than 10 and for identical liquid volumes, the time required to move up the walls increased slightly with increasing reorientation acceleration.

Comparison with results of Aerobee sounding rocket flight. - A flight study of low-gravity heat transfer in a spherical container (ref. 9) provided additional data on liquid reorientation. During that flight, reorientation from a reported zero-Bond-number condition was successfully made. The available data from the flight were reexamined by the authors of this report. The test containers were a 22.9-centimeter-diameter main sphere, 25 percent filled with liquid hydrogen, and a 2.54-centimeter-diameter secondary sphere, 40 percent filled with ethanol. A peak reorientation acceleration of 12×10^{-3} g was applied to the vehicle. During the 30 seconds allotted for reorientation, the reorientation acceleration dropped to about 4×10^{-3} g. This resulted in time averaged reorientation Bond numbers in the two spheres of 30 and 0.7.

The reorientation data obtained from the flight compared favorably with the results of this study. In particular, reorientation in both containers was axisymmetric. A geyser, which did not reach the opposite portion of the sphere, appeared in the main container (Bo_R of 30). Smooth reorientation was present with no geyser in the small sphere (Bo_R of 0.7). Symmetric mode oscillations were observed in both spheres. In the small sphere, a completely quiescent collected configuration was reached. The total collection time was approximately 10 seconds. The large sphere did not reach a quiescent collected interface. Oscillations of slowly decreasing amplitude were observed during the entire 30-second reorientation maneuver.

CONCLUSIONS

An experimental investigation of liquid reorientation in spherical containers (2.1 to 3.1 cm radii) by means of low-g accelerations (0.005 to 0.03 g) was conducted in the Lewis Research Center's 2.3-second drop tower. The liquids used had essentially zero-degree static contact angles on the surfaces of the spheres. The study was conducted at two initial interface conditions. One initial condition was a centrally located vapor bubble (i.e., the interface configuration in a sphere in a zero-Bond-number environment). A second initial condition was an essentially flat interface (i.e., the interface configuration in a relatively high-Bond-number environment). In each case, the reorientation acceleration resulted in a low reorientation Bond number ranging from 1.6 to 23.

The results show that reorientation in spheres was axisymmetric under both initial interface conditions. Liquid rebound, or geysering, can occur. And finally, large-amplitude, symmetric-mode oscillations occurred about the final collected interface position.

Because of the geyser phenomena, the large-amplitude collected-interface oscillations, and the environmental time limitations, total collection times could not be obtained in this study. Total collection times remain impossible to predict accurately. Drop-tower studies in this area can provide meaningful data, but only if the variables are restricted to specific values scaled to a particular vehicle and mission.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 23, 1968,
124-09-03-01-22.

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